GEOPHYSICAL RESEARCH LETTERS, VOL. 23, NO. 1, PAGES 1-4, JANUARY 1, 1996

Anisotropy in inner core attenuation: a new type of data to constrain the nature of the solid core

Annie Souriau
Observatoire Midi-Pyrénées, Toulouse, France

Barbara Romanowicz
Seismographic Station, UC Berkeley, Berkeley, California

Abstract. During the last decade, the presence of velocity anisotropy inside the inner core, with a fast axis parallel to the Earth's rotation axis, has been well established. The quantitative analysis of the amplitudes of waves which sample a particular region of the inner core, under Africa, but exhibit various orientations allows us to document and characterize the presence of anisotropy in attenuation. The analysis is based on a comparison of both amplitudes and travel times of the PKP(DF) wave, which samples the inner core, and the PKP(BC) wave, which has nearly the same path but bottoms inside the liquid core. The data reveal that the direction of strong attenuation correlates with that of fast velocity. When referred to the same epicentral distance and focal depth, the PKP(DF)/PKP(BC) amplitude ratio are about five times lower for paths tilted by 25° with respect to the Earth rotation axis, than for nearly equatorial paths. A clear negative correlation is observed between travel time and amplitude residuals, when the angle to Earth rotation axis varies. This first quantitative analysis, combined with experimental results on oriented crystals and mushy media, may bring important constraints on the mechanism responsible for anisotropy in the inner core.

Introduction

Evidence for anisotropy of seismic velocities inside the Earth's solid inner core has been established from several studies during the last decade [*Morelli et al.*, 1986; *Woodhouse et al.*, 1986; *Shearer et al.*, 1988; *Shearer and Toy,* 1991; *Creager*, 1992; *Song and Helmberger*, 1993; *Tromp*, 1993; *Shearer,* 1994]. These studies have established that waves propagating nearly parallel to the Earth's rotation axis are significantly faster than those propagating parallel to the equatorial plane, with travel time differences as large as 3 to 5 s [*Creager*, 1992; *Song and Helmberger,* 1993; *Shearer*, 1994; *Vinnik et al.*, 1994]. However, the exact geometrical pattern of this anisotropy and its depth variations are difficult to specify, because large parts of the inner core remain unsampled by seismic body waves [e.g. *Shearer*, 1994; *Su and Dziewonski*, 1995]. On the other hand, eigenmodes have a poor resolution in that part of the Earth [*Woodhouse et al.*, 1986; *Tromp*, 1993]. This poor knowledge of the characteristics of the anisotropy makes it difficult to specify what is the mechanism at its origin. A preferred orientation of anisotropic iron crystals, either in hexagonal closed-packed (hcp) phase, or in face-centered cubic (fcc) phase, or possibly another unknown phase, has often been invoked (see for example *Poirier* [1994], for a review). Perfectly aligned hcp-iron crystals would explain rather well the observed anisotropy [*Stixrude and Cohen,* 1995], but the physical process generating this alignment is still in debate. It could be related to either the magnetic field [*Karato*, 1993] , or to convection in the inner core [*Jeanloz and Wenk*, 1988; *Weber and Machetel*, 1992], or to mechanical effects directly related to Earth's rotation [*Stacey*, 1992]. An alternative explanation for the velocity anisotropy is the presence in the inner core of ellipsoidal liquid inclusions [*Doornbos*, 1974], with a preferred orientation due to inner core convection. This explanation is favored if a mushy zone, whose existence is postulated at the inner core boundary, extends deep inside the inner core [*Fearn et al.*, 1981].

Seismic velocities alone do not provide much information about the origin of anisotropy. For some of the mechanisms proposed above, an anisotropy in attenuation is also expected [*Peacock and Hudson*, 1990; *Carcione and Cavallini*, 1994]. A few previous observations have pointed out the very low amplitudes of waves propagating nearly parallel to the Earth's rotation axis inside the inner core (*Creager*, 1992; *Song and Helmberger*, 1993; *Cormier*, 1994]. These observations are however too scattered to provide useful constraints on attenuation since they sample different regions and could thus be potentially explained by effects of lateral heterogeneity on the paths. Only a comparison of data sampling the same region with various orientations would allow to distinguish between lateral heterogeneity and anisotropy. However, because the conditions for obtaining reliable amplitude data are drastic, such a geometry is not frequently found with the available datasets. In this study, we present the results of an investigation of the best sampled region of the Earth, located under west Africa. It is based on a joint analysis of the variations in seismic velocities and amplitudes, for rays bottoming with various orientations inside the inner core in this particular region.

Method and data selection

The study is based on a comparison of PKP(DF) waves, which propagate inside the inner core, with PKP(BC) waves, which have nearly the same path in the mantle, but have their turning point in the liquid core, or are diffracted along the inner core boundary. This method has been widely used in previous studies concerning the inner core velocity anisotropy or heterogeneity [*Cormier and Choy*, 1986; *Shearer et al.*, 1988; *Shearer and Toy*, 1991; *Creager*, 1992; *Song and Hemberger*, 1993] and inner core quality factor [e.g. *Niazi and Johnsón*,

Paper number 95GL03583
0094-8534/96/95GL-03583$03.00

1992; *Bhattacharyya et al.*, 1993]. The level of heterogeneity and anisotropy at the base of the liquid core is very low [*Stevenson*, 1987; *Roudil and Souriau*, 1993], thus the variations in the differential travel times of PKP(BC)-PKP(DF) and those in the amplitude ratios PKP(DF)/PKP(BC) may be ascribed to inner core heterogeneities or anisotropy. On the other hand, the possible influence of inner core heterogeneities is strongly diminished when selecting data bottoming in the same region.

The two core phases PKP(DF) and PKP(BC) are very close in time, they are well observed as two distinct phases in the distance range 147° - 160°. At about 151 degrees (depending on the Earth model), PKP(BC) becomes diffracted at the inner core boundary, and has generally too low an amplitude to be observed beyond 160°. The distance range 147-160° corresponds to an inner core sampling at depths 160 to 520 km below inner core boundary. For good quality observations, it is necessary in addition that the second arrival, PKP(BC), be not

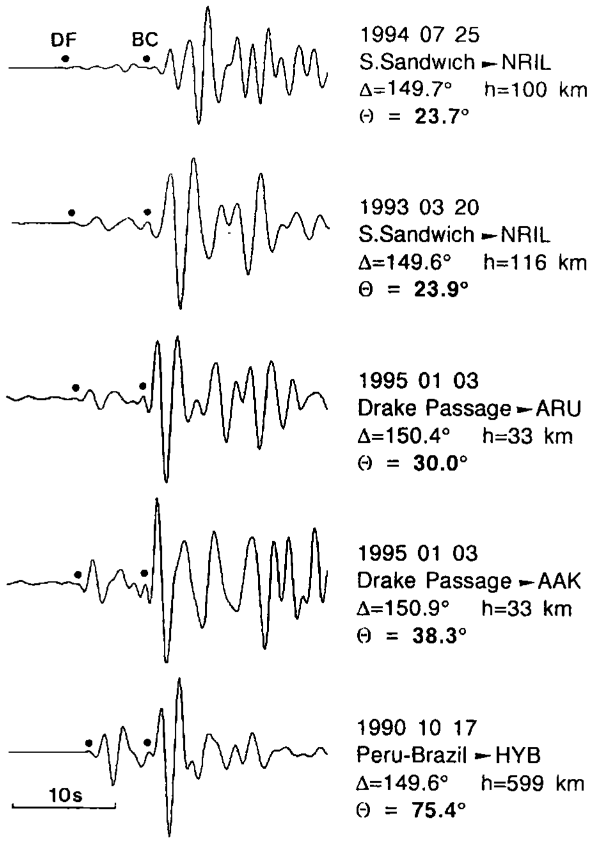

Figure 1. Examples of data collected at the IRIS and GEOSCOPE broadband networks. Vertical records, bandpass filtered at 2s period. The data correspond nearly to the same epicentral distance (Δ=150°), and have their turning point in the same region. The PKP(DF) arrival corresponds to a ray propagating inside the inner core. The PKP(BC) ray has nearly the same path inside the crust and the mantle, but has its turning point inside the homogeneous liquid core. It is used as the reference phase. The data correspond to increasing values of Θ, the angle of the DF ray inside the inner core with respect to the Earth's rotation axis. Note the decreasing (BC-DF) time delay and the increasing DF/BC amplitude ratio for increasing Θ-values. They indicate an anisotropy in seismic velocities and in attenuation, respectively: the direction parallel to the Earth's rotation axis corresponds to high velocities and strong attenuation inside the inner core.

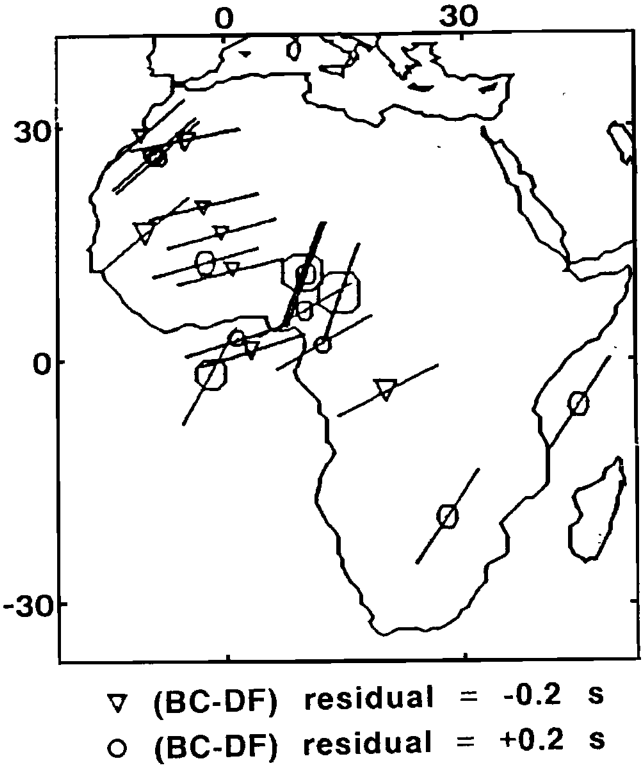

Figure 2. Geographic distribution of the data used in this study. The symbols represent the differential travel time residuals of PKP(BC) - PKP(DF), with respect to the reference Earth model PREM [*Dziewonski and Anderson*, 1981]. They are plotted at the turning point of the PKP(DF) ray. Circles correspond to positive residuals (high velocities inside the inner core), triangles to negative residuals (low velocities inside the inner core). The size of the symbols is proportional to the absolute value of the residuals. The bars indicate the PKP(DF) ray azimuth at its turning point.

contaminated by the depth phases of PKP(DF), first reflected on the Earth's surface. For this reason, we mainly used deep focus events.

The major difficulty is to find a region in the inner core which is well sampled with rays having various orientations with respect to the Earth's rotation axis. With the data available from the worldwide, broadband networks (mainly IRIS GSN and GEOSCOPE), it turns out that the best sampled inner core region is located beneath Africa. For GEOSCOPE, we selected all the available events in the period 1987 - 1994. For IRIS, we kept most of the data which were available since 1992. This gives a total number of 21 data, useful for both travel time and amplitude analyses. Figure 1 shows a few examples of these data, which are nearly at the same epicentral distance (Δ=150°), but exhibit different angles Θ with respect to the Earth's rotation axis. The influence of the velocity anisotropy is quite apparent: the time difference between DF and BC decreases for increasing Θ-values. We also note a spectacular increase of the DF/BC amplitude ratio when Θ increases.

Propagation times and amplitudes

Differential travel times of PKP(BC)-PKP(DF) are measured on the raw data using the shape similarity between the two phases. Their residuals with respect to the reference Earth model PREM [*Dziewonski and Anderson*, 1981] are reported on Figure 2 at the location of the ray turning point. Also reported is the azimuth of the ray at this point. As the turning points are close to the equator, azimuth and angle to rotation axis have nearly the same value. The (BC-DF) residuals decrease for increasing Θ (Figure 3a). The observed variation is close to that reported in previous papers [*Creager*, 1992; *Song and Helmberger*, 1993; *Shearer*, 1994]. It corresponds to an anisotropy slightly weaker than the uniform anisotropy model proposed by *Creager* [1992], which considers a velocity 3% faster in the polar direction than in the equatorial direction.

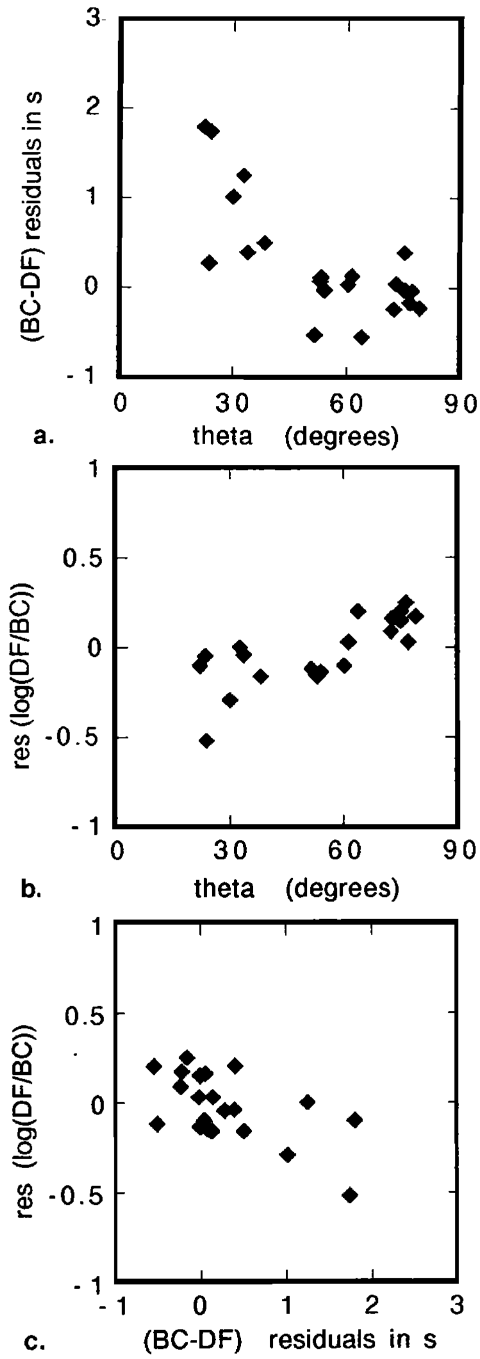

Figure 3. a- Differential travel time residuals of PKP(BC)-PKP(DF), as a function of the angle Θ of the DF path inside the inner core with respect to the Earth's rotation axis. The observed variation corresponds to anisotropy in seismic velocities; b- Residuals of log(DF/BC), where DF/BC denotes the amplitude ratio of the two waves at 3s period with respect to a reference Earth model which fits worldwide attenuation data. The variations with Θ reveal anisotropy in attenuation inside the inner core; c- correlation between the travel time and amplitude residuals: the high velocity axis corresponds to the strong attenuation axis. This relation may help constrain the origin of the anisotropy inside the inner core.

Amplitude ratios of PKP(DF)/PKP(BC) are frequency dependent even if attenuation is not frequency dependent [*Niazi and Johnson*, 1992]. We determined them at a period of 3s. It has been shown in a previous study that this period is a good compromise between shorter periods, for which the signal is more affected by scattering, and longer periods, for which PKP(DF) and PKP(BC) may overlap. The amplitude residuals are defined as the difference between the decimal logarithm of the observed amplitude ratio, and the one computed for the same distance and focal depth, at the same period, for a reference Earth model [*Souriau and Roudil*, 1995]. This reference model, which slightly differs from PREM, has been built in order to fit the attenuation data at the worldwide scale. It includes a constant velocity at the base of the liquid core, and a quality factor of 200 (instead of 440 for PREM) in the upper 100 km of the inner core [*Souriau and Roudil*, 1995]. The residuals of log(DF/BC) are plotted on Figure 3b as a function Θ. They clearly indicate a decrease of the attenuation in the inner core, when the ray angle with respect to Earth's rotation axis increases.

Discussion

Most of the PKP(DF) rays considered here sample nearly the same region in the inner core, due to the large size of the Fresnel zone for these rays. Thus, the observed variations may not be due to heterogeneities. They strongly suggest the presence of an anisotropy in attenuation inside the inner core: When referred to the same epicentral distance and to the same depth, rays tilted by about 25 degrees with respect to the Earth rotation axis have an amplitude about 5 times higher than those tilted by about 90 degrees.

It is worth noting that small amplitude variations, which mimic an anisotropy in attenuation, may also be induced by the anisotropy in velocity. In fact, the anisotropy in velocity distorts the wavefront as it propagates. This effect differentially focuses and defocuses the energy along the wavefront [*Samec and Blangy*, 1992]. However, this effect should remain small for the rather low velocity anisotropy, less than 3%, detected along the DF ray in the uppermost 500 km of the inner core. Thus, anisotropy in attenuation remains the most plausible candidate for explaining the observed amplitude variations. As shown from Figure 3c, the anisotropies in velocity and in attenuation are correlated: the strong attenuation axis corresponds to the axis of maximum velocity, nearly parallel to the Earth's rotation axis.

Attenuation in anisotropic media has been little studied. Most of the studies have focussed on crustal material, or on the low velocity layer of the mantle, or have concerned other fields in physics, in particular acoustics. Two kinds of media have been investigated: those made of anisotropic material [e.g. *Hosten et al.*, 1987; *Carcione and Cavallini*, 1990; *Samec and Blangy*, 1992], and those made of isotropic material containing fluid inclusions or cracks [*Schmeling*, 1985; *Peacock and Hudson*, 1990]. For an isotropic structure containing small ellipsoidal saturated cracks with a small aspect ratio, which could possibly represent a mush, the models predict that the P-wave low velocity axis corresponds to the axis of high attenuation [*Peacock and Hudson*, 1990]. This is opposite to what we observe. By contrast, studies concerning media made of oriented anisotropic crystals predict a correlation similar to what we observe for the inner core: for example, in an anisotropic clayshale medium, the low-velocity P-axis corresponds to the axis of low attenuation [*Carcione and Cavallini*, 1994], which is in this example the axis of symmetry of the medium. It is highly hazardous to transpose such results to inner core structure. However, these examples show that the positive correlation we find between anisotropy in velocity and anisotropy in attenuation may bring important constraints on the physical nature of the inner core. This may stimulate laboratory experiments, as well as modelling of anisotropic media at core conditions.

Acknowledgments. A.S. thanks D. Mainprice for helpful informations about anisotropy in attenuation. We thank an anonymous reviewer and P. Shearer for their reviews. This research was partially supported by INSU-DBT, UC Berkeley Seismographic station, and NSF EAR Grant #9417862. It is Seismographic Station contribution #95-7. A.S. salary is paid by CNRS (#47000).

References

Bhattacharyya, J., P. Shearer, and G. Masters, Inner core attenuation from short-period PKP(BC) versus PKP(DF) waveforms, *Geophys. J. Int.*, *114*, 1-11, 1993.

Carcione, J.M., and F. Cavallini, A rheological model for anelastic anisotropic media with applications to seismic wave propagation, *Geophys. J. Int*, *119*, 338-348, 1994.

Cormier, V.F., and G.L. Choy, A search for lateral heterogeneity in the inner core from differential travel times near PKP-D and PKP-C, *Geophys. Res. Lett.*, *13*, 1553-1556, 1986.

Cormier, V.F., Inner core structure inferred from body waveforms, *EOS Trans. Am. Geophys. Un.*, *75*, 67, 1994.

Creager, K.C., Anisotropy of the inner core from differential travel times of the phases PKP and PKIKP, *Nature*, 356, 309-314, 1992.

Doornbos, D.J., The anelasticity of the inner core, *Geophys. J.R. Astron. Soc.*, *38*, 397-415, 1974.

Dziewonski, A.M., and D.L. Anderson, Preliminary Reference Earth model, *Phys. Earth Planet. Inter.*, *25*, 297-356, 1981.

Fearn, D.R., D.E. Loper, and P.H. Roberts, Structure of the Earth's inner core, *Nature*, *292*, 232-233, 1981.

Hosten, B., M. Deschamps, and B.R. Tittmann, Inhomogeneous wave generation and propagation in lossy anisotropic solids. Application to characterization of viscoelastic composite materials, *J. Acoust. Soc. Am.*, *82*, 1763-1771, 1987.

Jeanloz, R., and H.R. Wenk, Convection and anisotropy of the inner core, *Geophys. Res.Lett.*, *15*, 72-75, 1988.

Karato, S., Inner core anisotropy due to the magnetic field-induced preferred orientation of iron, *Science*, *262*, 1708-1711, 1993.

Morelli, A., A.M. Dziewonski, and J.H. Woodhouse, 1986, Anisotropy of the inner core inferred from PKIKP travel times, *Geophys. Res. Lett.*, *13*, 1545-1548, 1986.

Niazi, M., and L.R. Johnson, Q in the inner core, *Phys. Earth Planet. Inter.*, *74*, 55-62, 1992.

Peacock, S., and J.A. Hudson, Seismic properties of rocks with distributions of small cracks, *Geophys. J. Int.*, *102*, 471-484, 1990.

Poirier, J.P., Physical properties of the Earth's core, *C.R. Acad. Sci. Paris*, *318-II*, 341-350, 1994.

Roudil, P., and A. Souriau, Liquid core structure and PKP station anomalies derived from PKP(BC) propagation times, *Phys. Earth Planet. Inter.*, *77*, 225-236, 1993.

Samec, P., and J.P. Blangy, Viscoelastic attenuation, anisotropy, and AVO, *Geophysics*, *57*, 441-450, 1992.

Schmeling, H., Numerical models on the influence of partial melt on elastic, anelastic and electric properties of rocks. Part I: elasticity and anelasticity, *Phys. Earth Planet. Inter.*, *41*, 34-57, 1985.

Shearer, P.M., Constraints on inner core anisotropy from PKP(DF) travel times, *J. Geophys. Res.*, *99*, 19,647-19,659, 1994.

Shearer, P.M., K.M. Toy, and J.A. Orcutt, Axi-symmetric Earth models and inner core anisotropy, *Nature*, *333*, 228-232, 1988.

Shearer, P.M., and K.M. Toy, PKP(BC) versus PKP(DF) differential travel times and aspherical structure in the Earth's inner core, *J. Geophys. Res.*, *96*, 2233-2247, 1991.

Song, X., and D.V. Helmberger, Anisotropy of the Earth's innner core, *Geophys. Res. Lett.*, *20*, 285-288, 1993.

Souriau, A., and P. Roudil, Attenuation in the uppermost inner core from broadband Geoscope PKP data, *Geophys. J. Int.*, *123*, 572-587, 1995.

Stacey, F.D., *Physics of the Earth* (Third edition), Brookfield Press, Brisbane, 513 pp, 1992.

Su, W., and A.M. Dziewonski, Inner core anisotropy in three dimensions, *J. Geophys. Res.*, *100*, 9831-9852, 1995.

Stevenson, D.J., Limits on lateral density and velocity variations in the Earth's outer core, *Geophys. J. Roy. Astron. Soc.*, *88*, 311-319, 1987.

Stixrude, L., and R.E. Cohen, High pressure elasticity of iron and anisotropy of Earth's Inner Core, *Science*, *267*, 1972-1975, 1995.

Tromp, J., Support for anisotropy of the Earth's inner core from free oscillations, *Nature*, *366*, 678-681, 1993.

Vinnik, L., B. Romanowicz, and L. Breger, Anisotropy in the center of the Earth, *Geophys. Res. Lett.*, *21*, 1671-1674, 1994.

Weber, P., and P. Machetel, Convection within the inner-core and thermal implications, *Geophys. Res. Lett.*, *19*, 2107-2110, 1992.

Woodhouse, J.H., D. Giardini, and X.-D. Li, Evidence for inner core anisotropy from free oscillations, *Geophys. Res. Lett.*, *13*, 1549-1552, 1986.

A. Souriau, Observatoire Midi-Pyrénées, Groupe de Recherche de Géodésie Spaitiale, 14 Avenue Edouard Belin, 31400 Toulouse, France. (e-mail: souriau@pontos.cnes.fr)

B. Romanowicz, Seismographic Station, UC Berkeley, Berkeley, CA 94720, USA. (e-mail: barbara@seismo.berkeley.edu)

(Received October 14, 1995; accepted October 25, 1995.)